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Modal Test/Analysis Correlation of Space Station Structures Using Nonlinear Sensitivity

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MODAL TEST/ANALYSIS CORRELATION OF SPACE STATION STRUCTURES USING NONLINEAR SENSITIVITY

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Abstract

The modal correlation problem is formulated as a constrained optimization problem for validation of finite element models (FEMs). For large-scale structural applications, a pragmatic procedure for substructuring, model verification, and system integration is described to achieve effective modal correlation. The space station substructure FEMs are reduced using Lanczos vectors and integrated into a system FEM using Craig-Bampton component modal synthesis. The optimization code is interfaced with MSC/NASTRAN to solve the problem of modal test/analysis correlation; that is, the problem of validating FEMs for launch and on-orbit coupled loads analysis against experimentally observed frequencies and mode shapes. An iterative perturbation algorithm is derived and implemented to update nonlinear sensitivity (derivatives of eigenvalues and eigenvectors) during optimizer iterations, which reduced the number of finite element analyses.

Introduction

The Space Station Freedom (SSF) substructure finite element models (FEMs) require validation against vibration test modes for launch and on-orbit coupled load analysis in support of the dynamic simulation team effort. The stowed configuration of the SSF and integrated equipment assembly are shown in Figures 1 and 2.

With the objective of improving correlation between test and analytical modes of vibration for a large-scale space structure, such as SSF, a constrained optimization formulation of the problem is presented. MSC/NASTRAN software with user's manual[1] is employed for the finite element analysis (FEA) to perform component modal synthesis (CMS) based on Craig-Bampton coupled loads methodology. Referring to the NASTRAN FEA outer loop iterations in Figure 3, the Optimizer postprocesses NASTRAN FEM modes to find the local minima for the modified FEM without appreciably changing the design variables of the as-built test analysis

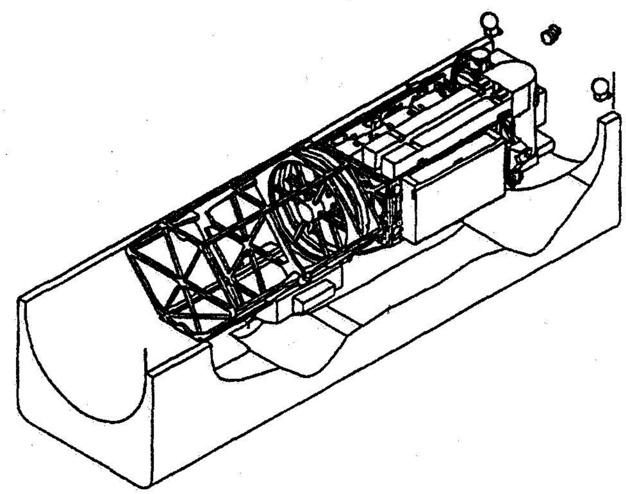

Figure 1. S3/S4 Cargo Element in Launch Package Configuration

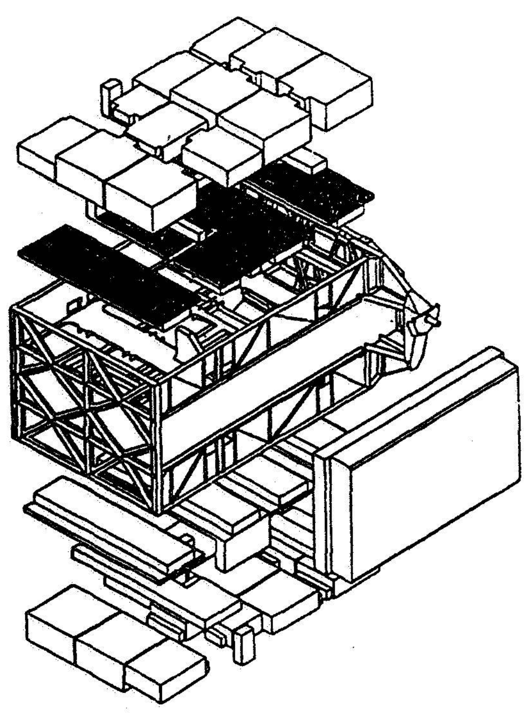

Figure 2. Space Station IEA and Substructures

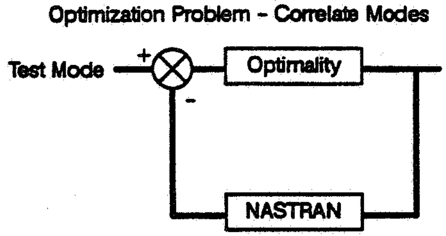

Figure 3. Space Station Modal Correlation

model. Both analytical frequencies and mode shapes are correlated against test modes and the FEM modified until correlation is satisfactory.

Optimum design of large-scale structures have been limited by the number of independent (or linked) design variables to less than 200, resulting from the increasing number of FEA iterations and partly from the commercial impracticability of repetitive eigenvalue analysis for updating eigenvalue/eigenvector sensitivity. A pragmatic method is presented in this paper to overcome this impracticability using higher order approximation based on novel perturbation techniques. The cost of performing either structural design optimization or FEM modal validation using optimality criteria[2,3] is seemingly independent of the number of design variables, unlike mathematical programming in Vanderplaats' ADS code.[4] This cost-effectiveness quality of number independence in optimality criteria may also exist with genetic search strategy proposed by Hajela[5] and interval arithmetic by Sepulveda and Schmit[6] in pursuit of global optima. The cost of repetitive eigenvalue analysis during optimizer iterations is avoided by substituting iterative perturbation algorithm of Van de Vooren[7] and Gupta, Newell, and Roberts[8] that updates eigenvalues, eigenvectors, and their sensitivity in the spirit of approximation concepts.[6] Patnaik, Guptill and Berke[9] discovered potential singularities in the constraint gradient matrix as a result of linear dependence among stress and displacement, but not necessarily frequency constraints, sufficient to prevent convergence to local minima. Armand and Lin[10] find that the Timoshenko beam modes are higher (than those with the NASTRAN Euler beam); mass moments of inertia and geometric stiffening resulting from preload in the SSF photovoltaic arrays was taken into account.

With frequency optimization or detuning, disjoint feasible spaces have been recognized,[6,11] making the global optimization problem a challenging combinatorial problem; $(m+1)^r$ frequency subspaces exist for r retained structural modes and m forcing frequencies. Allowing only one natural frequency to cross one forcing frequency, one needs to examine 2r contiguous frequency subspaces.

Testing of Space Systems and Components

Test correlation frequently succeeds in optimizing real life applications. Rocketdyne has production experience with acoustic and vibration tests of specific applications: Space Shuttle Main Engine (SSME), Kinetic Energy Vehicle (KEV), National Aerospace Plane (NASP) active coolant panel technology, SSF electric power system (EPS) and components. Test correlation by Becht[12] demonstrated that roughened seals enhance stability for the High-Pressure Fuel Turbopump (HPFTP) in the SSME; the test results included the coupled rotor-support structure interaction effects. Panossian[13] utilizes particle damping technology to alleviate unbalanced rotor vibration.

Component Modal Synthesis and Correlation

Effective correlation with valid test modes requires reasonable analytical modes. The process of integrating large-scale FEMs for system structural analysis and the need to perform extensive FEM model checks are addressed in previous papers.[8,14,15] CMS is preceded by model verification at each component level and synthesis step. Traditionally, a simple dynamics FEM is developed to achieve improved correlation against modal test data. The detailed superelement model can be reduced to an equivalent simple model using Guyan reduction,[16,17] Block Lanczos reduction,[8] or other suitable Ritz basis vectors.

Test Analysis Model (TAM) Generation

The TAM is the reduced FEM where the test modes will be correlated. The reduced degrees-of-freedom (DOF) must be determined to be representative of the full FEM structural model. Several techniques are often employed to identify system modes as follows:

1. **Driving Point Residue (DPR)**: The optimal shaker locations may be found using DPRs; that is, those DOF from where most of the modes could be excited. The mass matrix is not involved.

$$DPR_i(DOF_j) = \phi_i^2(DOF_j)/\omega_i$$

2. **Modal Assurance Criteria (MAC)**: The optimal measurement locations may be found using MAC; that is, those DOF where most of the modes can be observed. The mass matrix is not involved.

$$MAC_{ij} = (\phi_i \cdot \psi_j)^2 / \{(\phi_i \cdot \phi_i)(\psi_j \cdot \psi_j)\}$$

3. **Effective Modal Mass**: The effective modal mass contribution of a substructure or superelement participating in the system modes is helpful in

dealing with complex FEMs where visualization of modes is difficult. The formula (implemented in the form of NASTRAN DMAP) for the effective modal mass computation has been found useful as implemented in MSC/NASTRAN. Total effective mass for the observed test modes should exceed 85% of the total system mass along three orthogonal directions. The modes of the properly designed test fixture should not affect the target system modes by more than 2%. If the generalized mass is measured, this criterion is more useful.

4. **Cross Orthogonality (90/10)**: The diagonal terms of the matrix product of the transposed analytical modes, FEM mass matrix, and the test modes should exceed 0.90, indicating strong correlation between corresponding test and analytical modes. The off-diagonal terms should be less than 0.10; a larger value would indicate coupling between otherwise orthogonal modes. This criterion is useful when the mass matrix is representative of the as-built FEM.

5. **Modal Gain Factors**: Another criterion is to rank modes using control transfer functions in commercially available codes, such as COSTIN, EASY5, MATRIXx, based on the frequency separation between the structure modes and the exciting frequency of the forcing function.

Effect of Nonlinearities on Test Data

The nonlinear effects[18-20] of stick/slip friction in the SSF trunnion supports may cause significant shifts in the frequency spectrum of the target modes. In the case of the Centaur test,[15] the trunnions had stiff supports unlike the orbiter's flexible boundary supports; at low load levels, a significant nonlinear effect was attributed to the stiction/friction in the trunnions, but little effect was noticed at higher load levels in terms of the dead band traces of time-history response. In practice, the Ground Vibration Test (GVT) amplitude is so small that there is little evidence of slippage in fasteners or buckling of skin, and the mass should be adjusted to reflect the true as-built TAM.

Validation of Space Station FEMs

Large-scale finite element stress models of structures, such as SSF, are developed for the sake of including meticulous design detail. The more detailed the FEM, the higher the model fidelity, and the more difficult is the problem of modal validation of the FEM, largely because of inseparable local modes, complex or coupled modes, and unobservable spurious modes.

The modal test/analysis correlation problem is formulated as a mathematical programming (MP) primal problem solved by the ADS code,[4] and as a dual Lagrangian problem solved by Optimality Criteria (OC) code.[2] The NASTRAN[1] FEM of the SSF Integrated Equipment Assembly (IEA) with the test boundary conditions is modified using design sensitivity—derivatives of eigenvalues (vibration frequency) and eigenvectors (vibration modes) with respect to design variables (thicknesses, areas, moments of inertia, masses) in the physical FEM built from the production drawings. The vibration sensitivity derivatives are updated outside NASTRAN using an iterative perturbation algorithm during the inner optimization loop. Complete FEM analysis with MSC/NASTRAN is updated with the local minimum as an outer loop, and the optimization process is repeated until correlation is satisfactory.

Generalized Optimality Criteria

The objective and the constraints are often expressed as a first- or second-order Taylor series expansion.[2,3] Vance[19] has used a combination of Pade approximants (ratio of fourth-order polynomials) and curve-fitting techniques to estimate frequencies and mode shapes as a function of design thickness. Our aim is to develop recursive algorithm to design minimum weight structure or improve modal correlation based on the OC, using nonlinear perturbation techniques.

Ordinarily, a system of nonlinear algebraic equations is derived as Kuhn-Tucker conditions by setting to zero the first derivative of the Lagrangian, $L(x,\lambda) = f(x) + \Sigma(\lambda.g(x))$, with respect to design variables x and Lagrange multipliers λ. Recurrence relations are deduced to solve for x and λ's that represent presumably known active constraints. Gauss-Seidel iteration to update x and λ is recommended. Convergence is fast, making the algorithm efficient for large problems, since only a few FEM analyses are needed, especially with a good starting design. The formulation of the problem of modal validation of FEMs as an optimization problem requires choosing an objective function, design variables or control factors and constraint equations.

Objective. The objective is to adjust the design variables of the FEM so as to minimize the difference between the predicted analytical modes, ϕ, and the corresponding measured test modes, ψ. Ideally, without any modeling error, the test and analytical modes have perfect correlation; that is, the cross orthogonality with

respect to the analytical mass matrix, M, would be an identity matrix:

$$\{\phi_i\}^t M \{\psi_j\} = I$$

One object then is to minimize the matrix norm, $||f_1||$:

$$f_1 = \{\phi_i\}^t M \{\psi_j\} - I$$

Alternately, under the 90/10 cross-orthogonality test, the diagonal and the off-diagonal terms of matrix f_1 was numerically constrained so as not to exceed 0.10 to achieve term-by-term control within the optimizer as a series of inequality constraints rather than the single composite value as an objective function.

Mode Sorting Criteria. To identify which test mode ψ_j corresponds to which analytical mode ϕ_i, the value of the cross-orthogonality $\phi_i \cdot M \cdot \psi_j$ would be a maximum for the best (i,j) matching pair. For matrix multiplication $\phi_i \cdot M \cdot \psi_j$ to be meaningful, the test modes $\{\psi_j\}$ are sorted to be in the same order as the corresponding analytical modes $\{\phi_i\}$.

Scaling of Modes. The test and analytical modes are orthogonalized to a unit matrix before computing the difference between corresponding test and analytical modes. The modes ϕ and ψ were originally mass orthonormal and are difficult to compare for error visualization. Another reason for scaling modes is to enable direct application of the Van de Vooren–Gupta–Newell–Roberts (VGNR) formulae to update eigenvalues and eigenvectors resulting from a change in the superelement stiffness and mass matrix.

Multiobjective Optimization. Multiple objectives often arise with multidisciplinary optimization and a compromise among objectives is sought. In the case of modal correlation, another objective is to minimize the norm $||f_2||$ of the errors between each of analytical frequencies λ and corresponding test frequencies μ in addition to the difference between the n-dimensional analytical and test mode shapes.

$$f_{2i} = (1-\lambda_i/\mu_i)^{**}2 + (1/n)||\phi_i - \psi_i||/||\psi_i||$$

Multiple objectives f_1 and f_2 can be combined into a scalar objective function using a suitable weighting function in consideration of the coefficient of correlation. The cross-orthogonality between test and analytical modes can be reduced to a coefficient of correlation for weighting the correlatable modes using the reciprocal of the coefficient of correlation.

Design Sensitivity

Several papers have advanced new methods for approximating alternate forms of eigenvector derivatives. The dynamic response sensitivity capability in version 67 of MSC/NASTRAN avoids eigenvector derivatives and the associated overhead using Rayleigh–Ritz shape functions instead.[1] Noor et al[20] use residual static modes and derivatives to account for the higher-order effects of modal truncation in vibration response sensitivity. The perturbation method for eigenvector derivatives discussed in this paper is equally applicable to handle the vibration response optimization problem, especially where explicit modal superposition is employed.

Finite Difference Gradients. A 1% change in design variables is usually adequate to numerically calculate vibration sensitivity gradients using the nonlinear perturbation technique. Forward, backward, or central differences have been used and compared. Wherever necessary, the central-difference method is used for improved accuracy in numerical differentiation over the forward or backward difference. However, it would be cost prohibitive to solve the complete FEM repeatedly for eigenvalues and eigenvectors for change in each design variable to calculate eigenvalue and eigenvector sensitivity using finite differences. The perturbation procedure in this paper is cost effective because it updates the previously calculated eigenvalues and eigenvectors for perturbation in linked design variables (through substructure stiffness and mass matrices) using an iterative perturbation algorithm. Following are a few other analytical derivative schemes reported by earlier developers.

Eigenvalue/Eigenvector Sensitivity. The eigenvalue first-order derivative can be derived by implicit differentiation of the generalized eigenvalue problem and premultiplication with the eigenvector. The second-order eigenvalue derivative would involve the eigenvector derivative. The eigenvector derivative formula by Fox and Kapoor[11] requires a complete set of eigenvectors; the approximate truncated set often does not work well and is not valid for repeated roots. The modified formula by Fox and Kapoor requires decomposition of a fully populated large matrix and has numerical difficulties. Nelson's method[1] only requires one mode at a time and can solve for eigenvector derivatives of multiple eigenvalues using decomposition of a sparse matrix; however, there are numerical difficulties. Mills-Curran[11] takes first and second derivatives of the original equations of motion to generalize Nelson's method but is too complex to code and is computationally intensive in view of the next two algorithms.

Rayleigh–Quotient Algorithm.[21] It uses the modal energies $U = (\phi_i \cdot K \cdot \phi_i)$ and $T = (\phi_i \cdot M \cdot \phi_i)$ as the

intermediate response quantities, which are linear functions of the intermediate variables—A (area) and I (inertia)—to approximate the eigenvalue $\lambda = U/T$, the Rayleigh-Quotient. The convergence is rapid based on wider move limits because of the linearity of the approximation. However, eigenvectors $\{\phi_i\}$ are assumed invariant and eigenvector sensitivity is neglected during the optimizer iterations, unlike the perturbation method of the next section. On the other hand, several experts have determined that eigenvectors and their gradients should be updated more frequently during the optimizer iterations for effective modal validation of FEMs largely because of the nonlinear nature of the eigenvalue problem; that is, the objective and constraints cannot be linearly approximated directly in terms of the design parameters of the FEM. The Rayleigh-Quotient approximation is unconservative to the extent it overestimates the eigenvalue, which frequently causes the FEA frequency to violate its lower bound. To make the approximation of modal energies T and U more conservative, one is recommended to use linear and reciprocal variables for the lower limit, and reciprocal and linear variables for the upper limit.

Iterative Perturbation Algorithm.[7,8] The recursion formulae may be derived from first-order perturbation of the equilibrium equation and the generalized eigenvalue problem. The issue of whether to include higher-order terms tends to be problem-dependent. For example, an improved form of first-order Van de Vooren perturbation formula[7] to approximate ith updated eigenvalue λ_i'' and updated eigenvector ϕ_i'' can be easily derived as follows: Assume perturbations k_e and m_e in element stiffness and mass to the generalized eigenvalue problem $K{\bullet}\phi = \lambda{\bullet}M{\bullet}\phi$ resulting in $(K+ke){\bullet}\phi_i'' = \lambda_i''{\bullet}(M+me){\bullet}\phi_i''$. For ith eigenvalue and jth component of the eigenvector, our first-order formulae are:

$$\lambda_i'' = \{\lambda_i + (\phi{\bullet}k_e{\bullet}\phi)_{ii}\}/\{1 + (\phi{\bullet}m_e{\bullet}\phi)_{ii}\}$$

$$\xi_{ji} = \{\beta_{ji} - \alpha_{ji}{\bullet}\lambda_i''\}/\{(1 + \alpha_{jj})(\lambda_i'' - \lambda_j'')\}$$

where $\beta_{ji} = (\phi{\bullet}k_e{\bullet}\phi)_{ji}$, $\alpha_{ji} = (\phi{\bullet}m_e{\bullet}\phi)_{ji}$, and $\phi_i'' = \phi{\bullet}\xi_i/||\xi_i||$.

The effects of adding higher order terms and updating recursively on stability of convergence are being evaluated heuristically. These updates have obvious advantages over the Rayleigh-Quotient approximation in that updated eigenvectors are available based on using updated eigenvalues, improving the quality of otherwise nonlinear approximations. It should be pointed out that the perturbed equations can be solved exactly as a linear system of equations in eigenpair (λ_i'', ξ_{ji}) for the additional cost of inverting (for updating each eigenpair) a real symmetric matrix of order equal to number of modes to avoid Pade approximants.[19]

Constraint Deletion. It is useful to delete nonactive constraints; i.e., where the response ratios are below 0.7 (that is, the inequality side constraints are not within 30% of being violated).

Move Limits. Because the gradients are valid only in the vicinity of the current iteration, tighter move limits on design variables as iterations progress (50% initially, 5% near minima) helps avoid drift too far from the local minimum. Thus, move limits protect against bad approximations, e.g., encountered with linear approximation of nonlinear objectives and constraints. Larger move limits with good quality approximations, such as those based on the iterative perturbation algorithm presented do speed up convergence by requiring fewer FEA to achieve design economy.

Convergence Rate. Approximation methods speed up convergence by requiring fewer FEA using wider move limits during the optimizer iterations. Move limits can be tightened for nonlinear problems, as indicated by the discrepancy between the approximate values of the objective and constraints as calculated by the optimizer (upon convergence to a local minima) and those exact values as predicted by the FEA before the next optimizer cycle. Such a discrepancy should be minimal or below the acceptable tolerance near the optimum. Convergence to a local minimum is overcome by updating the FEM with the converged values of the design variables and by performing the complete eigenvalue analysis.

Stability of Convergence.[22-23] The spectral radius of the amplification matrix between two successive updates by the iterative perturbation algorithm must be less than unity. Dias[22] perturbs each random variable by 10% of one standard deviation. Loss of stability could arise if the perturbed solution drifts too far from the unperturbed state.

Summary of Results

The SSF orbital replacement units of Remote Power Control Module (RPCM) undergoing 0.5 g^2/Hertz random signature test on an electromagnetic shaker table is shown in Figure 4, and other SSF ORUs such as Local Data Interface (LDI), underwent sine sweep from 20 to 2000 hertz. The modal test to analysis correlation confirmed the occurrence of resonant peaks and damping. The SSME turbopump rotor, stator, and impeller modal correlation effort based on laser mode shape measurements is shown in Figure 5, in connection with High

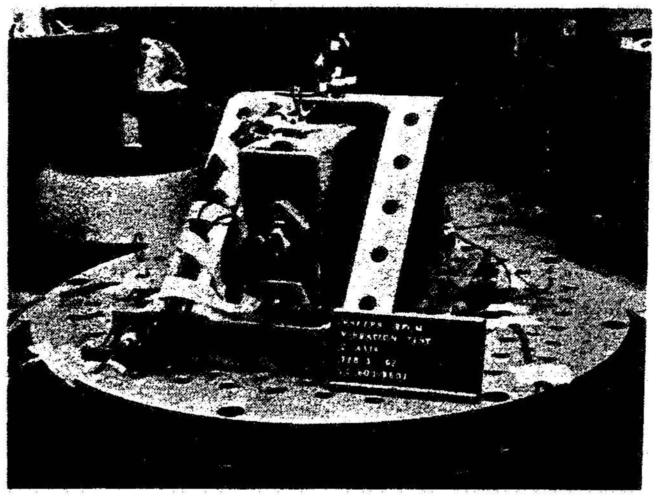

Figure 4. SSF RPCM Shaker Table Setup—Seven Accelerometers

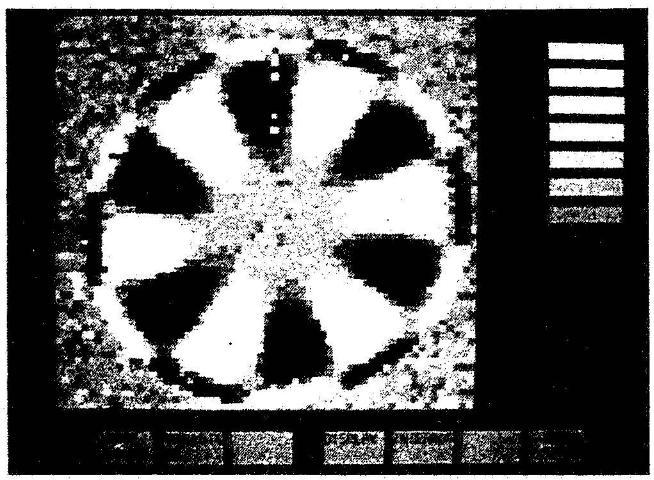

Figure 5. Low Pressure Fuel Turbopump (LPFTP) Test Mode

Cycle Fatigue (HCF) life prediction, crack investigation, and identification and avoidance of resonant modes.

The software test bed for validation of SSF FEMs (the IEA in particular) using test modes is developed as a postprocessor to MSC/NASTRAN. It updates frequencies, mode shapes, and their derivatives for perturbation in the design variables. It is coupled with the ADS and OC codes for optimization and is being coupled with the neural net expert system simulator.[24] At this time, the addition of residual static modes and their derivatives is not completely implemented and tested to evaluate the effect of higher order modes on vibration response correlation. Figures 6 and 7 exemplify a plate benchmark FEM for testing the above-implemented software test bed. It shows the correlation of nine analytical modes and test modes before and after optimization. The opti-

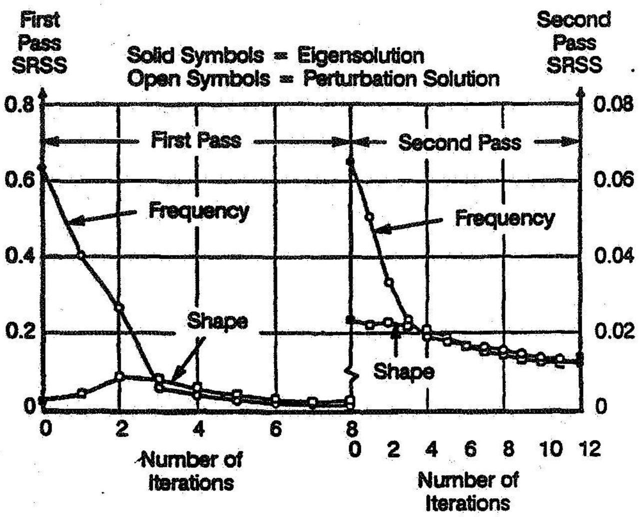

Figure 6. Optimizer Iterations and NASTRAN Analyses

mizer iterations are separated by NASTRAN analysis upon convergence to a local minima; only three NASTRAN analyses were required.

A 10-bar truss problem with four lumped masses was optimized using mode shape error and frequency constraints by Rula Coroneos at NASA-Lewis Research Center (LeRC) successfully validating the OC code against SUMT mathematical programming code in continuing support of this software development effort. The modal test data for the IEA is not yet available to perform final validation of the IEA FEM. There are three IEAs (Figure 2) in the SSF that support ORU boxes in the vicinity of the photovoltaic arrays.

Conclusion

In summary, the development of NASOPT software system as a postprocessor to MSC/NASTRAN using optimality and mathematical programming codes for optimization coupled with nonlinear perturbation algorithms makes possible cost-effective modal test validation of space station substructure FEMs, avoiding the cost impracticability associated with repetitive conventional eigenvalue analysis requirements. The neural network simulation, which requires several optima for training the expert system, is under development and appears promising for the simulation of several SSF configurations pending future numerical verification.

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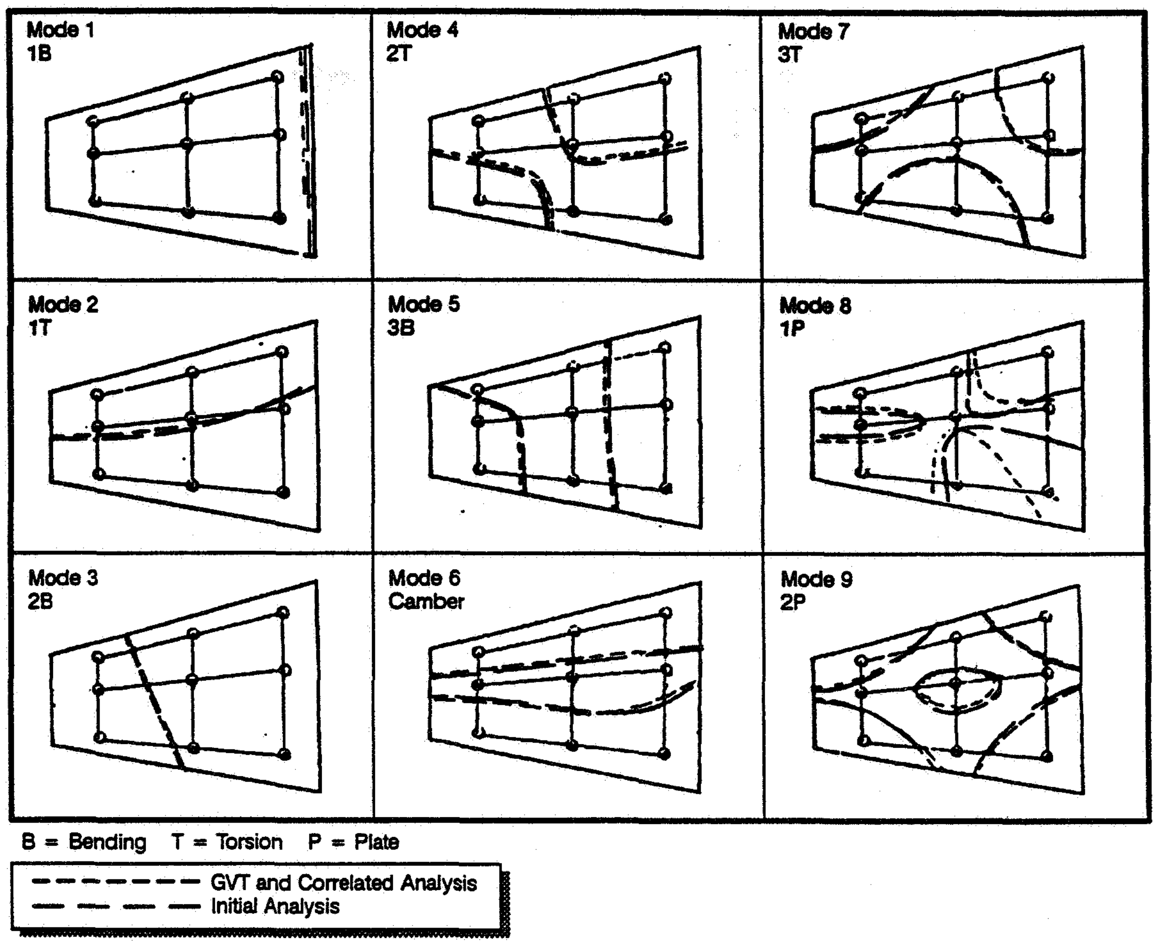

Figure 7. Optimizer Iterations and NASTRAN Analyses – A Correlation of Nine Analytical Modes and Test Modes Before and After Optimization.

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13. ABSTRACT ***(Maximum 200 words)***
The modal correlation problem is formulated as a constrained optimization problem for validation of finite element models (FEMs). For large-scale structural applications, a pragmatic procedure for substructuring, model verification, and system integration is described to achieve effective modal correlation. The space station substructure FEMs are reduced using Lanczos vectors and integrated into a system FEM using Craig-Bampton component modal synthesis. The optimization code is interfaced with MSC/NASTRAN to solve the problem of modal test/analysis correlation; that is, the problem of validating FEMs for launch and on-orbit coupled loads analysis against experimentally observed frequencies and mode shapes. An iterative perturbation algorithm is derived and implemented to update nonlinear sensitivity (derivatives of eigenvalues and eigenvectors) during optimizer iterations, which reduced the number of finite element analyses.

14. SUBJECT TERMS
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